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This paper addresses applied procedures for nonlinear aerodynamic model development and extraction from flight data for the S-3B Viking aircraft. The entire analysis procedures, from dynamic flight test data management to final blending and validation of the upgraded aerodynamic model, was performed within the Integrated Data Evaluation and Analysis Systems (IDEAS) developed by SAIC. IDEAS is a powerful database management system and analysis software containing a full complement of flight data preprocessing, calibration, simulation, model estimation, model verification, and validation tools.

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NONLINEAR AERODYNAMIC MODEL DEVELOPMENT AND EXTRACTION FROM FLIGHT TEST DATA FOR THE S-3B VIKING

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Abstract

This paper addresses applied procedures for nonlinear aerodynamic model development and extraction from flight data for the S-3B Viking aircraft. The entire analysis procedure, from dynamic flight test data management to final blending and validation of the upgraded aerodynamic model, was performed within the Integrated Data Evaluation and Analysis System (IDEAS) developed by SAIC. IDEAS is a powerful database management system and analysis software containing a full complement of flight data preprocessing, calibration, simulation, model estimation, model verification, and validation tools.

A variety of parameter identification (PID) techniques were employed to develop a global, fully nonlinear longitudinal and lateral-directional aerodynamic model. This effort included total aerodynamic coefficient reconstruction, equation error analysis for initial model structure development, and output error analysis for final model tuning.

Available S-3B PID flight data spanned a Mach range of 0.23 - 0.60 covering an adequate range of angle of attack for both nonlinear longitudinal and lateral-directional analyses. Regions outside the identified model envelope were described by blending with the original S-3B aerodynamic database to create a full envelope model.

Aircraft configurations investigated included cruise, maneuver, takeoff, and landing flap settings as well as retracted and extended landing gear. Standard flight test maneuvers were flown under each configuration and are described herein. The available data allowed for the successful extraction of component coefficients for aircraft lift, sideforce, pitching, rolling, and yawing moments resulting in a simulation with high aerodynamic fidelity.

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Introduction

The S-3B is a high-wing, twin engine U. S. NAVY aircraft produced by Lockheed. It has been in service since 1974. Current S-3B flight simulator models have been shown to be insufficient for pilot training in such tasks as aerial refueling, field and carrier approaches, and landings.[1] Consequently, SAIC was involved in an overall aerodynamic model simulation upgrade for the S-3B operational flight trainer (OFT) with the final goal of increasing model fidelity in the aforementioned flight regimes. Although not outlined in detail within this paper, SAIC was also responsible for additional upgrades regarding the TF-34 engine model, aircraft weight and balance formulation, and appropriate implementation of aircraft equations of motion and atmospheric models. Flights performed in the Summer of 1996 at the Naval Air Warfare Center, Aircraft Division, Patuxent River, MD resulted in a wealth of flight test data appropriate for PID purposes.

Flight test data collected for the purpose of aerodynamic parameter estimation typically consists of inertial and air-relative sensor outputs. Prior to performing parameter estimation, or traditional data reduction, it was necessary to evaluate and correct the measured data to ensure kinematic consistency of the inertial sensors as well as accuracy of the critical air-relative parameters. Consequently, a rigorous post-flight data calibration study was performed within IDEAS. Resulting corrections, in the form of biases and/or scale factors, were applied to the appropriate inertial and air-data sensors to arrive at a consistent set of data suitable for PID purposes.[2]

Additional data preprocessing resulted in overall aircraft weight and balance, as well as engine thrust information, for each PID maneuver. Given this information, tools within IDEAS allowed for the extraction of total aerodynamic force and moment coefficient histories for each PID maneuver by distinguishing them from those due to thrust.

Test data from maneuvers of comparable configuration were placed into analysis groups with ample data made available to span a suitable range of

the flight test envelope. Initial aerodynamic model structures were developed through analysis of these groups using an equation error extraction technique in IDEAS known as Athena. Athena was used to express the overall aerodynamic forces and moments as linear combinations of stability derivatives and/or increments. In addition, the capabilities of Athena allow for such terms to be modeled with nonlinear functionalities by employing basis spline functions. The resulting model was installed in a simulation of the airframe in question within IDEAS and used in further PID studies.

This newly developed aerodynamic model was further adjusted through estimation of increments to appropriate coefficients using an output error technique. This step was necessary to deal appropriately with any estimate biases resulting from the equation error procedure. Within IDEAS, this technique involves the use of a nonlinear least-squares optimization algorithm known as LSIDNT coupled with a version of the S-3B OFT containing the aerodynamic upgrade obtained using Athena.

The final identified model was blended with the baseline S-3B aerodynamic data package to result in a full envelope model upon which validation studies were performed.

Overall, PID analysis resulted in updates for both model structure and aerodynamic coefficients of lift and side force as well as pitching, rolling, and yawing moment coefficients. The upgraded model retains the thrust and drag performance parameters measured by the Flight Vehicle Simulation Branch of the Naval Air Systems Command. [3,7]

Each of the total aerodynamic coefficients follows a similar basic structure in that they consist of a series of incremental effects. These contributions include effects due to a basic aerodynamic coefficient, air-relative orientation, aircraft stability axis angular rates, control surface positions, and weapon stores.

The following sections examine the required data preprocessing, model structure development, and aerodynamic model extraction techniques in detail.

Available Flight Test Maneuvers

Standard PID maneuvers were chosen from the S-3B dynamic flight test database for the purpose of aerodynamic model extraction. Maneuvers under investigation included pilot applied all axis control doublets, all axis 3-2-1-1's, bank to bank aileron/spoiler rolls, and bank to bank aileron rolls. These maneuver classes were performed in blocks at each aircraft configuration investigated including cruise, maneuver, takeoff, and landing flap settings as well as retracted and extended landing gear. All maneuvers were flown with wing pylons in place and no additional external loads. The maneuver blocks contained the following back-to-back maneuvers at each flight condition and aircraft configuration:

- 360° Coordinated Heading Change Turn
- Longitudinal Stick Doublet
- Longitudinal Stick 3-2-1-1
- Lateral Stick Doublet (Aileron / Spoiler Interconnect Active)
- Lateral Stick 3-2-1-1 (Aileron / Spoiler Interconnect Active)
- Directional Pedal Doublet
- Directional Pedal 3-2-1-1
- Lateral Stick Bank to Bank Roll Attitude Capture (Aileron / Spoiler Interconnect Active)
- Lateral Stick Bank to Bank Roll Attitude Capture (Aileron Only)

The coordinated heading change turn that precedes each block of PID maneuvers was instrumental in the data calibration process as it provided valuable information regarding the magnitude and direction of atmospheric winds.[2] However, they were not analyzed during the PID process as they did not contain adequate mode excitation. The stick and pedal doublets were designed to appropriately excite the aircraft short period and dutch roll modes. The lateral stick bank to bank roll attitude captures were flown with both the aileron / spoiler interconnect active as well as inactive (aileron excitation only). This provided valuable information allowing for the differentiation between aileron and spoiler roll control / adverse yaw power.

A total of 56 individual PID maneuvers were separated into a series of 5 longitudinal and 5 lateral-directional analysis groups within IDEAS. Each group contained a collection of appropriate maneuvers from the list above that were flown under identical aircraft configuration. The configurations represented by the analysis groups are as shown:

- Cruise Flap Setting / Landing Gear Up
- Cruise Flap Setting / Landing Gear Down
- Maneuver Flap Setting / Landing Gear Up
- Takeoff Flap Setting / Landing Gear Down
- Landing Flap Setting / Landing Gear Down

Such analysis groups are instrumental during the PID process in that they present a wealth of information, through collections of PID maneuvers, to the estimation algorithm allowing for the extraction of a global aerodynamic model.

Dynamic Flight Test Data Preprocessing

Previous studies within IDEAS examined pertinent channels from each maneuver for data

dropouts and/or signal wrapping. Appropriate tools within the IDEAS Data Preprocessing And Reconstruction (DATPAR) toolbox were employed to correct such anomalies when they occurred.

In addition, previous extensive calibration studies within IDEAS resulted in inertial and air-data sensor adjustments, in the form of biases and/or scale factors, applied to the appropriate flight data to develop a set of consistent test data.[2]

Finally, DATPAR tools were used to compute a variety of important histories for each maneuver including stability axis angular rates, dynamic pressure, ambient temperature, true airspeed, Mach, air relative velocities, air relative body axis accelerations, and angular accelerations.

Total Aerodynamic Force and Moment Extraction

A variety of data is necessary to successfully extract total aerodynamic force and moment coefficients from flight data. These data consist of body axis angular rates and accelerations, body axis linear accelerations, dynamic pressure, body axis engine produced forces and moments, as well as aircraft mass and inertia data. In addition, to facilitate transferring the overall moments to a specific reference point, about which the aerodynamic model is to be developed, the center of gravity location for each maneuver must be determined.

Appropriate angular rate, angular acceleration, linear acceleration, and dynamic pressure data were acquired during DATPAR preprocessing as outlined in the previous section. Suitable information regarding aircraft mass characteristics as well as body axis engine forces and moments had to be determined.

To complete this task the baseline S-3B OFT was installed as a simulation running within the IDEAS environment. This version of the OFT included a new weight and balance module updated by SAIC to more accurately model the S-3B BuNo. 159743 experimental loading.[4] Aerodynamic model updates resulting from this work would later be applied to this version of the simulation. Characteristics such as aircraft mass, CG position, and airframe inertia were acquired by running this version of the OFT within the IDEAS environment. Appropriate loading conditions (fuel, stores, etc.) were set as per each individual PID maneuver to be employed for model development. This process involved trimming the simulation at the initial conditions per each maneuver and overriding with flight recorded control deflections during run time. The initial baseline simulation runs provided a preliminary look into the strengths and weaknesses of the original OFT aerodynamic model by allowing a comparison between pertinent simulated and recorded aircraft responses.

Similarly, engine body axis forces and moments for each maneuver were determined by running a stand-alone upgraded simulation of the TF-34 engines within the IDEAS environment.[5] In this case, quantities such as pressure and inertial altitude, ambient temperature, reconstructed true airspeed, and engine fan speeds were overridden using preprocessed and recorded flight data. The upgraded engine model was later incorporated into the final upgraded S-3B OFT.

With all necessary data made available to extract the total aerodynamic moment and force coefficients a variety of IDEAS tools were employed resulting in overall aerodynamic lift, drag, sideforce, pitching moment, rolling moment, and yawing moment coefficient histories with respect to the aircraft CG per PID maneuver. All body axis total force coefficients were reconstructed assuming a rigid body aircraft with negligible effects due to spinning engine rotors.

Additional IDEAS tools were used to transfer all reconstructed body axis aerodynamic moments to the desired reference point about which the aerodynamic model would be developed. This transference involves the incremental effects due to the reconstructed body axis aerodynamic forces about the aircraft CG being offset from the desired aerodynamic reference center. Finally, since the baseline S-3 OFT aerodynamic model was defined about the stability axis the corresponding moment coefficients were transferred about that axis system.

Aerodynamic Model Structure Development and Extraction Using Equation Error

Estimation Algorithm

The next stage of analysis entailed the use of an equation error PID technique to extract a new set of aerodynamic stability derivatives for the S-3B. The equation error tool in IDEAS, known as Athena, is capable of expressing the overall aerodynamic force and moments as linear combinations of stability derivatives and/or incremental coefficients. In addition, Athena allows these terms to be modeled with nonlinear dependencies through the use of spline basis functions. The algorithm uses singular value decomposition and divides the information matrix into observable and unobservable sub-spaces. Athena estimates the parameters based on the magnitude of the singular values associated with each parameter in principal component axes and converts them back to the physical domain.

This technique assumes the model may be represented as a set of linearly combined, time-independent parameters with the following structure:

$$y = A p + v \quad (1)$$

For aerodynamic model estimation, vector **y** represents the total non-dimensional force and moment coefficients. The parameter vector **p** represents the stability and control derivatives under estimation, and the regressor matrix **A** contains the independent variables.

The output statistics are provided in the form of a fit percentage based upon the Theil's inequality coefficient statistic (U) defined as:

$$U = \frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N}(\hat{y}_i - y_i)^2}}{\sqrt{\frac{1}{N}\sum_{i=1}^{N}(\hat{y}_i)^2} + \sqrt{\frac{1}{N}\sum_{i=1}^{N}(y_i)^2}} \quad (2)$$

N is the total number of points in the residual vector. Theil's inequality coefficient represents the ratio of the root mean square fit error and the root mean square values of the estimated and actual signal summed together. The value of U always falls between 0 and 1, with 0 indicating a perfect fit and 1 the worst fit.

The Athena fit percentage (F), a measure of signal fit quality, is defined as follows:

$$F = 100(1 - U) \quad (3)$$

A 100% fit represents a perfect match with the measured data.

Additionally, Athena breaks the fit error into bias (U_b), variance (U_v), and covariance (U_c) proportions as follows:

$$U_b = \frac{(\bar{\hat{y}} - \bar{y})^2}{\frac{1}{N}\sum_{i=1}^{N}(\hat{y}_i - y_i)^2}$$

$$U_v = \frac{(\sigma_{\hat{y}} - \sigma_y)^2}{\frac{1}{N}\sum_{i=1}^{N}(\hat{y}_i - y_i)^2} \quad (4)$$

$$U_c = \frac{2(1-\rho)\sigma_{\hat{y}}\sigma_y}{\frac{1}{N}\sum_{i=1}^{N}(\hat{y}_i - y_i)^2}$$

Where ρ and σ represent the correlation coefficient and standard deviation respectively.

$$\rho = \frac{1}{\sigma_y \sigma_{\hat{y}} N}\sum_{i=1}^{N}(\hat{y}_i - \bar{\hat{y}})(y_i - \bar{y})$$

$$\sigma_x = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x - \bar{x})^2} \quad (5)$$

The bias proportion presents the deviation of the average values of the simulated and measured data acting as a measure of model systematic error. The variance proportion acts as a measure of the model's ability to duplicate the variability in the true system. The covariance proportion is a measure of non-systematic error. Note that these three proportions sum to 1, with the ideal fit having U_b and U_v close to zero, with U_c close to 1.

These fit statistics act as a measure of accuracy and/or certainty in the proposed model formulation under investigation and provide clues into the effectiveness, or lack thereof, of adjustments introduced in the model structure.

An additional strength of this algorithm is its ability to analyze multiple segments of information, in this case PID maneuvers, at once. This allows for the extraction of global models from analysis groups of multiple PID maneuvers. Overall, this procedure is a fast, single pass algorithm that results in good base model structure determination.

Algorithm Application

In this study Athena was employed intensively to extract initial parameter estimates for lift, sideforce, pitching moment, rolling moment, and yawing moment coefficients given the kinematically consistent dynamic flight data and previously extracted aerodynamic total force and moment coefficients. The ability of Athena to estimate nonlinearities in coefficient trends using basis spline functions was exercised by analyzing groupings of PID maneuvers with the goal of determining a global aerodynamic model. Sufficient data spanning a range of Mach and angle of attack was made available to the algorithm providing a wealth of information.

Placement of spline knot locations is crucial. Knots should be placed within regions about which sufficient data is available for the breakpoint in question. In this study, knot locations were predominant for aircraft α and Mach throughout all force and moment model buildups. As a result, when analyzing a group of PID maneuvers, knot locations for angle of attack and Mach were distributed evenly such that they fell within appropriate values represented collectively for data within that group.

Not only was Athena successful at extracting the basic aerodynamic coefficients but it was also used to estimate incremental effects on the base model parameters due to flap and landing gear deployment. This was accomplished by adding incremental coefficients in the model formulation. Sample aerodynamic moment coefficient structures identified in this work using Athena are shown in Figure 1. The coefficients are shown to contain functionality in Mach, angle of attack, as well as extended landing gear and flap setting effects.

As is often the case in aircraft system identification several control surfaces lacked adequate excitation to facilitate successful extraction of their aerodynamic effects. Due to the lack of independent excitation for the horizontal stabilizer and rudder tab surfaces during the maneuvers, their effects were held constant at original OFT model values.[7] In addition, high correlation between aircraft angle of attack rate and body axis pitch rate required that aerodynamic coefficient effects by the former be fixed to original OFT values while effects of the latter were estimated.

The overall model identification process in Athena began with the initial definition of all force and moment aerodynamic model structures for the Cruise Configuration / Gear Up (CCGU) case. This model would be developed using the Cruise Flap Setting / Landing Gear Up analysis group in IDEAS. Each axis for the total force and moment aerodynamic coefficients reconstructed from flight data was examined separately using Athena. Initial model structures were as simple as possible containing no functionalities for the aerodynamic stability derivatives. The resulting Athena fit percentage and Theil's fit statistics for these simple models were retained and used as a basis of comparison for future model structures. The functionality and/or structure of each total coefficient model was then methodically expanded and identified within Athena. Coefficient functionalities investigated were based upon those expressed in the original OFT aerodynamic model as well as those deemed plausible by experience. The final CCGU aerodynamic force and moment models were chosen as those with the best increase in Athena fit percentage and most favorable Theil's fit statistic information (U_b, U_v, and U_c).

The base aerodynamic force and moment models resulting from analysis of the CCGU case would act as the a priori structures and values for the next analysis phase. From these base models incremental aerodynamic effects due to various flap settings, as well as landing gear extension, would be estimated. The previously identified cruise force and moment aerodynamic models were frozen within Athena while the remaining analysis groups were examined. The four remaining PID maneuver groupings represented various flap configuration settings as well as landing gear deployment. Again, with the base cruise models frozen within Athena the fit percentage and Theil's fit statistic information were recorded for the remaining analysis groups. Incremental effect coefficients were then methodically added to the frozen cruise model within Athena and estimated. These added terms modeled the effect of static flap position and/or extended landing gear on prominent coefficients currently existing in the CCGU Athena developed model. Again, the fit percentage and appropriate Theil's fit statistics were monitored to examine added coefficient increment effects on the fit quality. Similarly, flap and landing gear incremental effect coefficients investigated were based upon structures expressed in the original OFT aerodynamic model as well as those deemed plausible by engineering judgement.

As an overall example of this estimation process using Athena consider the sub-coefficient structure of the stability axis total rolling moment coefficient displayed in Figure 1. The base CCGU aerodynamic model was found to contain a significant aerodynamic bias term (C_{l_o}) that varied with Mach. This was consistent with pilot comments regarding a persistent, and noticeable, aircraft left wing down roll-off during straight and level flight for this particular aircraft. All maneuvers recorded a significant level of aileron trim set by the flight crew to counter the left wing down tendency.. Additional terms in the CCGU roll model include standard coefficients modeling the effects of pertinent control surfaces such as rudder ($C_{l\delta r}$), aileron ($C_{l\delta a}$), differential spoiler ($C_{l\delta sp}$), and rudder trim tab ($C_{l\delta tr}$). The remaining base model terms involve the dihedral effect ($C_{l\beta}$), roll damping (C_{lps}), and the effect due to yaw rate (C_{lrs}).

An analysis group of 18 lateral-directional PID maneuvers was examined during the development of the stability axis rolling moment coefficient cruise configuration model within Athena. The final model structure, as outlined in Figure 1, resulted in an Athena fit percentage (F) of 86.8% with fit error proportioned into 0% bias (U_b), 1.7% variance (U_v), and 98.3% covariance (U_c) for the analysis group as a whole. This indicates the developed model does not contain systematic error and system variability is emulated with good accuracy. A sample history comparison between flight reconstructed and Athena model estimated stability axis total rolling moment coefficient may be seen in Figure 2 for a lateral stick doublet flown under cruise conditions.

The remaining four lateral-directional analysis groups were examined for rolling moment model development. No significant rolling moment effects were determined due to extended landing gear. However, as many of the rolling moment coefficients

are strongly affected by wing lift and airflow distribution, particularly wing mounted lateral control surfaces, significant incremental adjustments to the model were necessary when examining the extended flap configuration analysis groups. For example, as wing panel lift increases with flap deployment incremental changes in the aileron and spoiler effectiveness ($\Delta C_{l\delta_a}$ and $\Delta C_{l\delta_{sp}}$) were determined. In fact, flap deployment was found to increase aileron effectiveness overall with a maximum increase of 23.5% at takeoff setting (δ_F=25°) while trailing off to a 16.2% increase in landing configuration (δ_F=35°). Spoiler effectiveness followed an identical trend with a steady, and considerable, increase in effectiveness of 54.6% in takeoff and 43.8% in landing flap configurations respectively. Similarly, a maximum 8.5% increase in roll damping (ΔC_{lp}) was found to occur in the takeoff flap configuration trailing off to a 4.9% increase in landing configuration. The increase in roll damping is as expected. C_{lp} is primarily driven by increased lift generated by the downard-rotating wing as its angle of attack is artificially increased. This may also be the reason for the lower increase in roll damping at full flap deflection in that downward wing motion may reach a less effective relative angle of attack. The dihedral effect ($\Delta C_{l\beta}$) and roll due to yaw (ΔC_{lr}) were enhanced by flap deflection with their greatest increases in magnitude of 7.1% and 11.6% respectively in landing flap configuration.

As an example of fit quality achieved with flaps deployed consider the analysis group of 6 lateral-directional PID maneuvers in the landing flap, gear down configuration. The final Athena model structure incremental coefficients for rolling moment resulted in an Athena fit percentage (F) of 88.4% with fit error proportioned into 0% bias (U_b), 0.8% variance (U_v), and 99.2% covariance (U_c) for the analysis group as a whole. A sample history comparison between flight reconstructed and Athena model estimated stability axis total rolling moment coefficient may also be seen in Figure 2 for a lateral stick doublet flown under landing flap, gear down conditions.

All total force and moment coefficients were studied in this manner resulting in a new preliminary aerodynamic model for the S-3B. Due to any unidentified measurement errors among the independent variables (particularly the control surface deflections, etc.) and non-uniform distribution of the regressors, the parameters output by this estimation technique may be biased. Consequently, this new model was tuned through employment of an output error estimation algorithm as discussed in the next section.

Model Adjustments Using Output Error

Estimation Algorithm

The output error optimization tool within IDEAS is the robust, nonlinear least-squares algorithm LSIDNT.[6] This algorithm works to minimize the standard least-squares cost function given a defined set of residuals to consider. This tool works in cooperation with a flight dynamics simulation within the IDEAS environment.

Algorithm Application

Recall the equation error PID analysis of the previous section resulted in an updated aerodynamic model for the S-3B. This upgraded model was coded into the S-3B non-linear 6 degree of freedom (DOF) simulation within IDEAS and was run by trimming to flight recorded initial conditions and overriding appropriate control deflections. These runs were performed on representative longitudinal, lateral, and directional PID maneuvers at different Mach, angle of attack, and landing gear/flap configurations. The resulting simulation output was visually compared with flight data to deduce areas where the new model required adjustment (e.g., additional damping, control authority, etc...).

Overall, the Athena generated model was found to be quite representative. However, some adjustments were necessary. Again, visual comparison between the new simulation output and calibrated flight data gave good clues as to what terms in the aerodynamic model required alteration. Final adjustments were made using the output error approach within IDEAS to estimate incremental coefficients applied to the existing ATHENA generated model terms.

Unknown incremental variables were placed throughout the aerodynamic model affecting Athena derived parameters under question within the new simulation. Consider an example where directional model characteristics were examined to uncover a need for changes in yaw damping, directional stability, and/or rudder control power. In this case the following terms were added to the total aerodynamic yawing moment coefficient within the updated 6 DOF simulation in IDEAS:

$$\begin{aligned}\Delta C_n(\beta) &= \left(C_{n_{\beta_{Athena}}} + \Delta C_{n_{\beta_{Out.Err.}}}\right)\beta \\ \Delta C_n(r_s) &= \left(C_{n_{r_{s\,Athena}}} + \Delta C_{n_{r_{s\,Out.Err.}}}\right)\left(\frac{r_s b}{2V}\right) \qquad (6) \\ \Delta C_n(\delta_r) &= \left(C_{n_{\delta_{r_{Athena}}}} + \Delta C_{n_{\delta_{r_{Out.Err.}}}}\right)\delta_r\end{aligned}$$

Individual lateral stick and rudder pedal input PID maneuvers were examined to investigate required incremental corrections to directional stability ($\Delta C_{n\beta}$) and yaw damping (ΔC_{nrs}) coefficients. In addition, the rudder pedal input PID maneuvers also produced estimates for incremental corrections to rudder control power ($\Delta C_{n\delta r}$). Resulting coefficients from each analysis were plotted versus Mach with any trends noted. As maneuvers were flown at 5 distinct Mach points the incremental output error estimates were averaged at each flight condition to yield the final estimates shown in Figure 3. This figure presents results for each directional correction in the form of the ratio of correction required to original equation error estimate. This presents the output error results in the form of a relative change in magnitude allotted by the estimates. Recall from Figure 1 the original equation error estimate for directional stability ($C_{n\beta}$) was constant throughout the flight envelope. However, Figure 3 clearly indicates an increasing trend in directional stability ($\Delta C_{n\beta}$) as Mach increases. This functionality was not uncovered during the equation error analysis. Figure 3 also indicates a fairly constant increase in rudder control power ($\Delta C_{n\delta r}$) is required throughout the flight envelope while a significant envelope wide constant decrease in yaw damping (ΔC_{nrs}) is also required.

Additional model adjustment estimates were determined as appropriate for all axes in a similar fashion. Once the incremental estimates had been obtained, these adjustment parameters were applied to the Athena base model resulting in the final extracted PID model. Of course, this model is valid for a certain region within the aircraft flight envelope. In order to obtain full envelope coverage this model update was blended into the original S-3B OFT aerodynamic database to yield the final production OFT.

Upgraded Simulation Validation

Sample response history plots comparing the SAIC developed fully blended flight model with the original S-3B training simulation are shown in Figures 4 - 6 for a longitudinal, directional, and lateral doublet maneuver compared with flight data. The baseline and upgraded OFT responses are a result of setting the aircraft loading and configuration in the simulation to match each PID maneuver, trimming the simulation, and propagating while overriding control surface deflections with flight test signals. Each figure contains recorded flight data, original S-3 OFT, and SAIC upgraded S-3 OFT response histories. This allows for an excellent comparison between the fidelity of both models. Marked improvement is evident in all axes.

The longitudinal responses of Figure 4 indicate higher fidelity in static trim for angle of attack. The longitudinal peak pitch rates are also captured more realistically in the updated simulation.

The directional maneuver of Figure 5 shows an improvement in yaw axis damping and natural frequency during the transient response. Similarly, improvement is also found in roll axis damping and natural frequency. Capture of initial roll rate peaks has improved with the updated model.

The greatest increase in fidelity is shown by the lateral maneuver of Figure 6. The updated model produces an excellent match with recorded flight responses both during the initial lateral control input as well as throughout the transient response. This can be said for both the primary roll axis and cross axis yaw responses.

Conclusions

A nonlinear aerodynamic model has been successfully developed, and installed within a nonlinear 6 DOF OFT, for the S-3B Viking. Early model structure determination employed an equation error estimation algorithm. Final model adjustments were determined using an output error estimation technique. The entire process, from database management of the flight data, to final validation of the upgraded OFT, was completed within the IDEAS environment.

The SAIC developed nonlinear aerodynamic model presents significant improvements in both longitudinal and lateral-directional characteristics of the trainer. The short period and dutch roll modes, control authority, and trim characteristics of the new model were greatly affected. These improvements result in simulation handling qualities representative of the true aircraft in both high and low gain flight tasks within the flight envelope where test data is available.

References

1 - SAIC, "Analysis and Upgrade of Device 2F92B Aerodynamic Model Using Flight Data Collected During 1992 From S-3A BuNo 159736," SAIC Report No. 1393-2994-3, May 1995.

2 - Paris, A. C., and Alaverdi, O. "Post-Flight Inertial And Air-Data Sensor Calibration", AIAA Atmospheric Flight Mechanics Conference, Boston 1998, AIAA-98-4450

3 - NATOPS Flight Manual Navy Model S-3B Aircraft, NAVAIR 01-S3AAB-1, August 1996.

4 - SAIC, "Upgraded Mathematical Model Report for Device 2F92B", SAIC Report No. 01-1393-9226-E005, May 1999.

5 - SAIC, "Upgraded Propulsion Model for S-3B Device 2F92B", SAIC Report No. 1393-6296-D001, April 1999.

6 - Dennis, J. E. Jr., Gay, D. M., and Welsch, R. E., "An Adaptive Nonlinear Least-Squares Algorithm," *ACM Transactions on Mathematical Software*, Vol. 7, No. 3, September 1981, pp 348-368.

7 - S-3A Aerodynamic Stability and Control and Flying Qualities Report, Lockheed Report 23462-3, Vol. 3, Revision E, December 1975.

$$C_m = C_{m_o}(M) + C_{m_\alpha}(M)\,\alpha + C_{m_{\delta_e}}(M)\,\delta_{\mathrm{e}} + C_{m_{\delta_{e_t}}}(M)\,\delta_{\mathrm{e_t}} + C_{m_{\delta_H}}(M)\,\delta_{\mathrm{H}} +$$

$$C_{m_q}(M)\frac{q\bar{c}}{2V} + C_{m_{\dot\alpha}}\frac{\dot\alpha\bar{c}}{2V} + \Delta C_{m_{o_{pylon}}} + C_{m_{\delta_F}}\delta_F + \left(C_{m_{o_{LG}}} + C_{m_{\alpha_{LG}}}\alpha\right)\delta_{\mathrm{LG}}$$

$$C_n = C_{n_o} + \left(C_{n_\beta} + C_{n_{\beta_{LG}}}\delta_{LG} + \Delta C_{n_\beta}(\delta_F)\right)\beta + C_{n_{\delta_r}}\delta_r + C_{n_{\delta_a}}\delta_a +$$

$$\left(C_{n_{\delta_{sp}}} + \Delta C_{n_{\delta_{sp}}}(\delta_F)\right)\delta_{sp} + \left(C_{n_{r_s}} + \Delta C_{n_{r_s}}(\delta_F)\right)\frac{r_s b}{2V} + C_{n_{p_s}}(\alpha)\frac{p_s b}{2V} + C_{n_{\delta_{tr}}}\delta_{tr}$$

$$C_l = C_{l_o}(M) + \left(C_{l_\beta} + \Delta C_{l_\beta}(\delta_F)\right)\beta + C_{l_{\delta_r}}(\alpha)\delta_r + \left(C_{l_{\delta_a}} + \Delta C_{l_{\delta_a}}(\delta_F)\right)\delta_a +$$

$$\left(C_{l_{\delta_{sp}}} + \Delta C_{l_{\delta_{sp}}}(\delta_F)\right)\delta_{sp} + \left(C_{l_{r_s}} + \Delta C_{l_{r_s}}(\delta_F)\right)\frac{r_s b}{2V} + \left(C_{l_{p_s}}(\alpha) + \Delta C_{l_{p_s}}(\delta_F)\right)\frac{p_s b}{2V} + C_{l_{\delta_{tr}}}(\alpha)\delta_{tr}$$

Figure 1: Aerodynamic moment coefficient model structures identified using the Athena equation error tool.

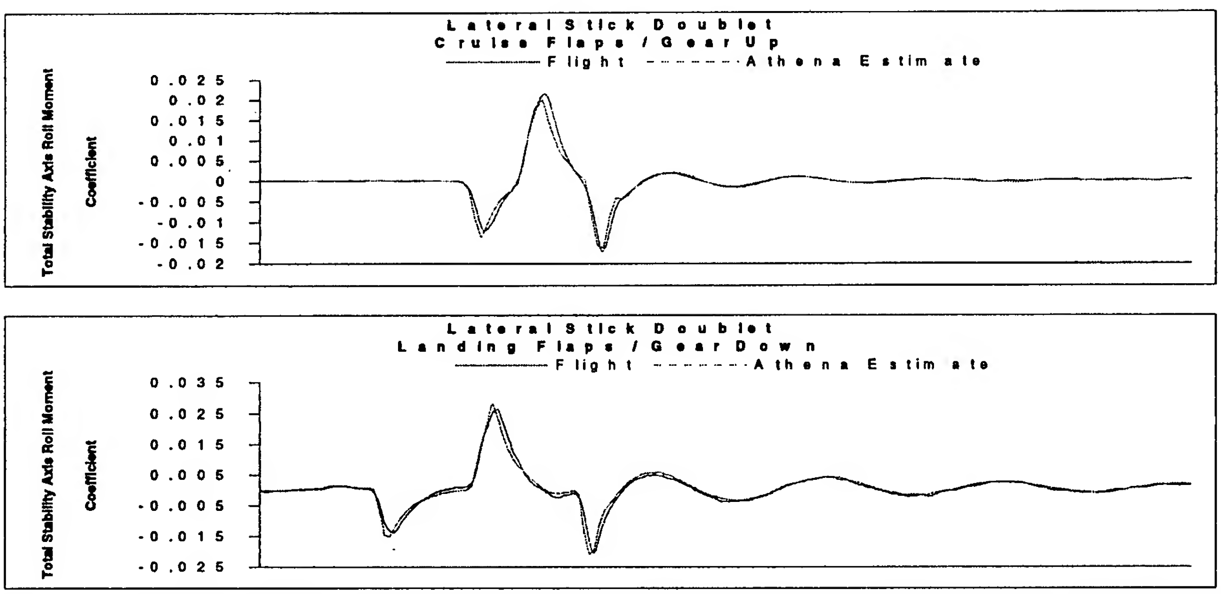

Figure 2: Comparisons between Flight reconstructed and Athena estimated total rolling moment coefficients for both Cruise and Landing configurations.

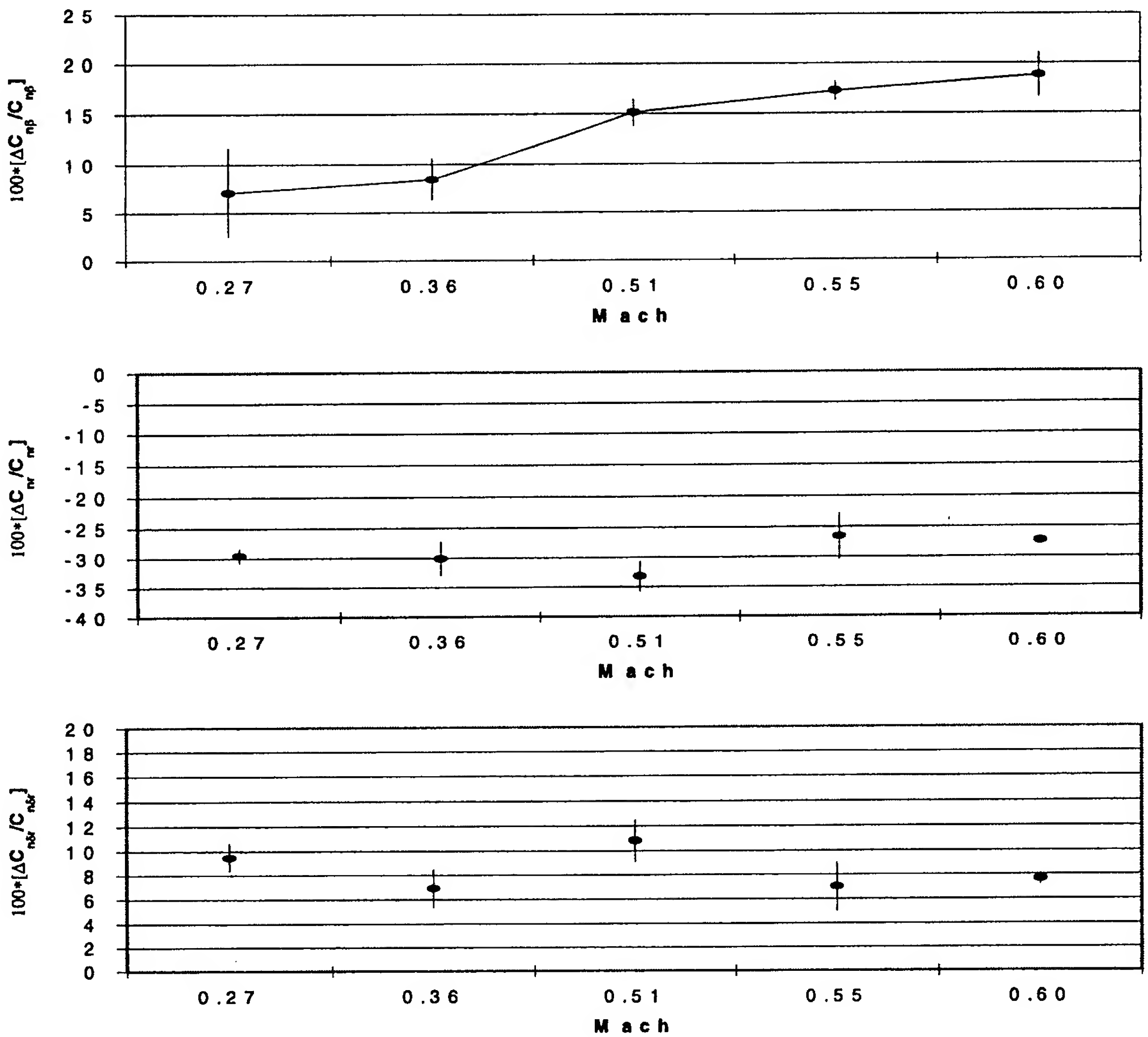

Figure 3: Output error estimates indicating relative changes in magnitude of various yawing moment coefficients as a function of Mach.

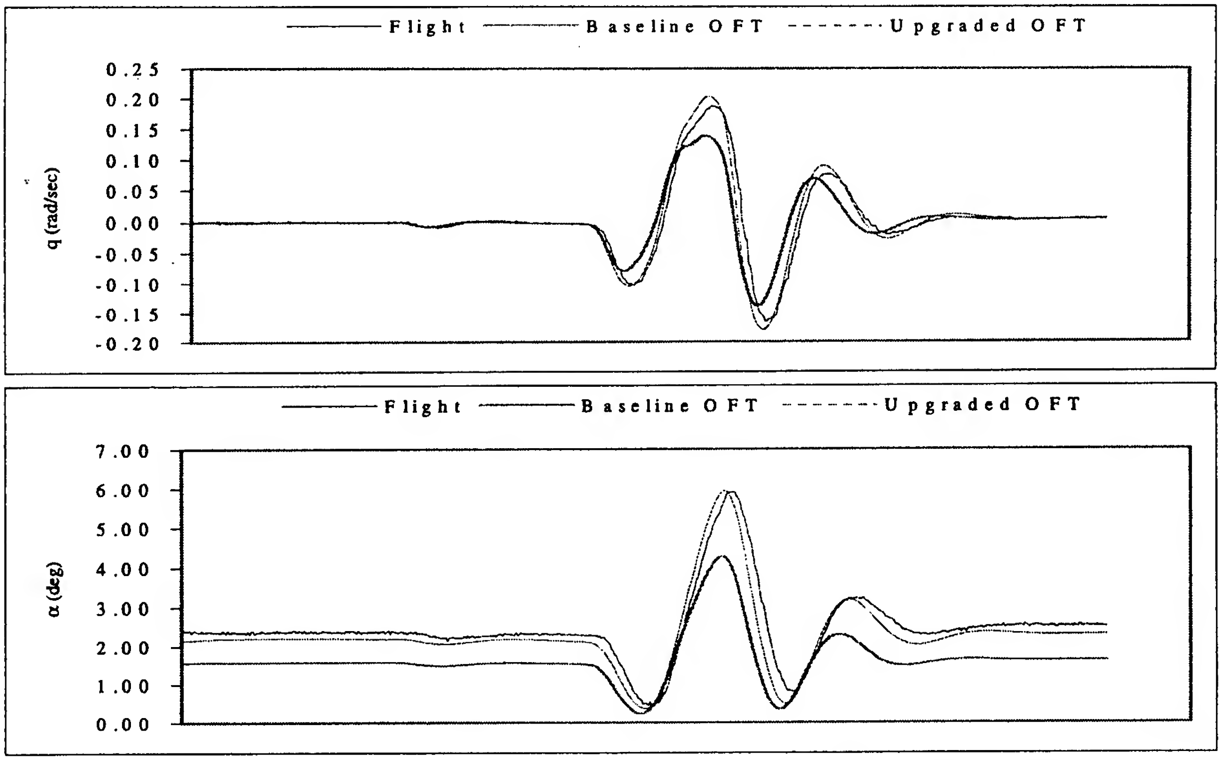

Figure 4: Response history comparison between baseline OFT and upgraded OFT with flight data for a longitudinal stick doublet.

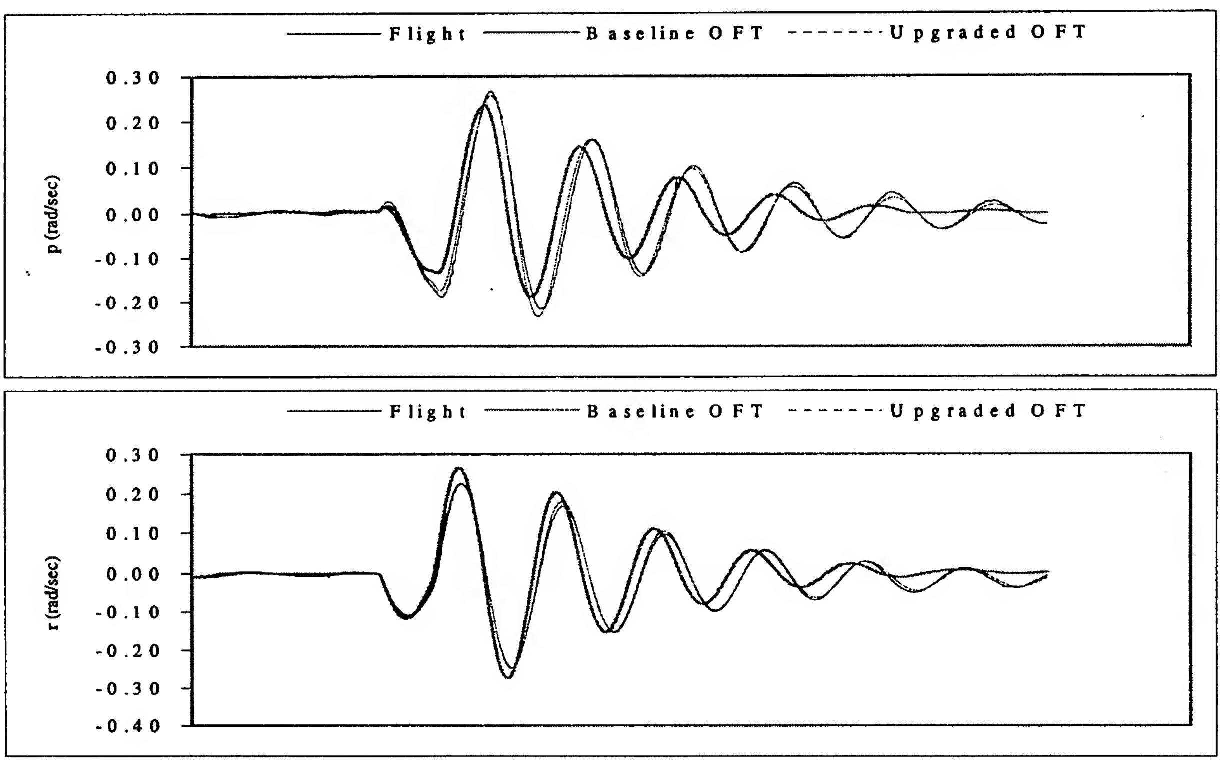

Figure 5: Response history comparison between baseline OFT and upgraded OFT with flight data for a directional pedal doublet.

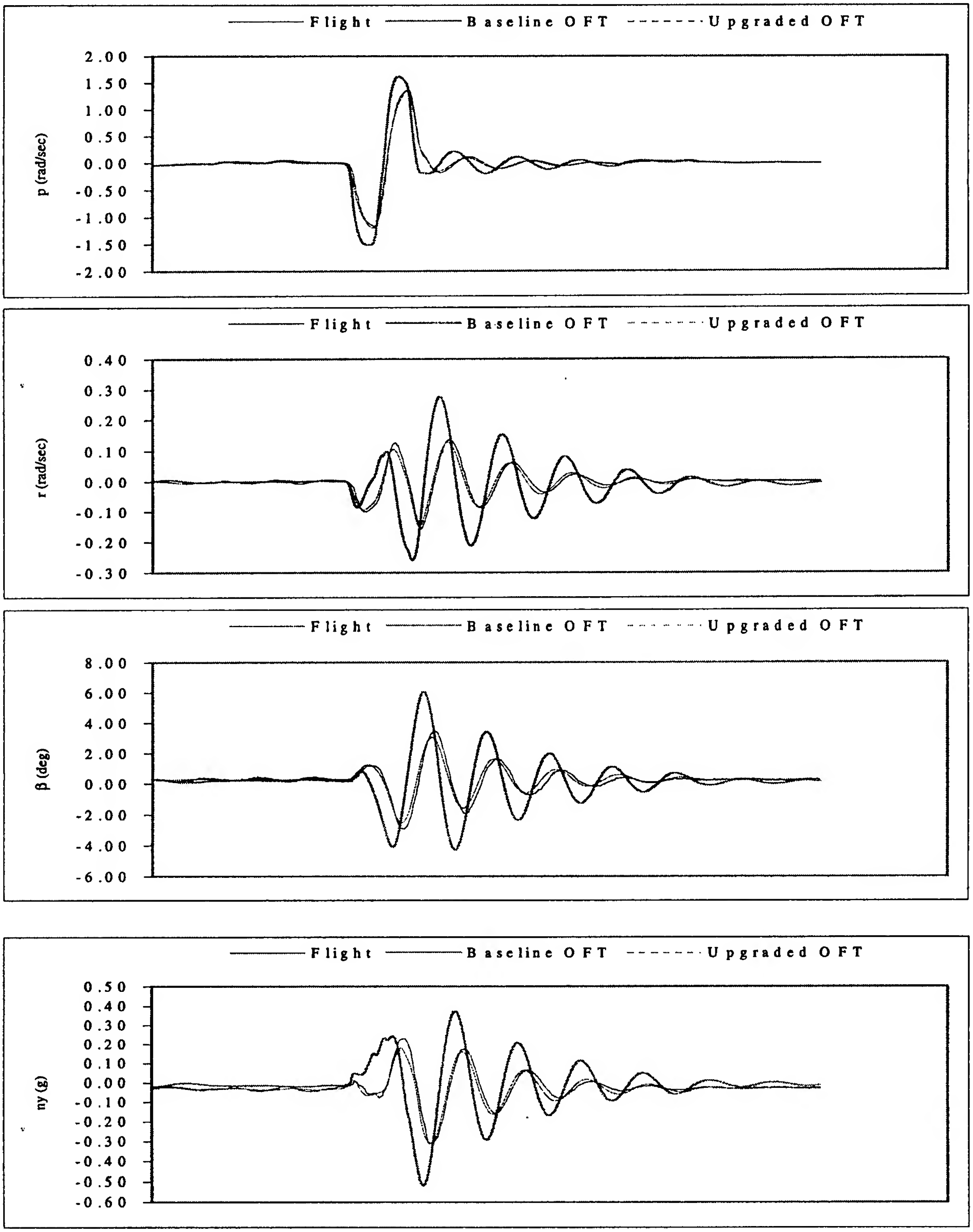

Figure 6: Response history comparison between baseline OFT and upgraded OFT with flight data for a lateral stick doublet.

NON-LINEAR AERODYNAMIC MODEL DEVELOPMENT AND EXTRACTION FROM FLIGHT TEST DATA FOR THE S-3B VIKING

by

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INTRODUCTION

- S-3B Viking OFT Flight Improvement Program
- Integrated Data Evaluation and Analysis System
- Data Pre-processing
- System Identification / Parameter Estimation techniques
- Results and conclusions

S-3B VIKING OFT FLIGHT IMPROVEMENT PROGRAM

- U. S. Navy service since 1974
- Tasked with overall Operational Flight Trainer upgrades
  - TF-34 engine model
  - weight and balance formulation and characteristics
  - equations of motion and atmospheric model formulations
  - aerodynamic model updates
- Flight tests include
  - 360° heading change turns
  - all axis doublets and 3-2-1-1's
  - bank to bank aileron & aileron / spoiler rolls
- Instrumentation
  - CAINS II inertial navigation system
  - installed nose boom with flow angle vanes / pitot probe
  - production sensors

INTEGRATED DATA EVALUATION AND ANALYSIS SYSTEM (IDEAS)

- Database management system
  - maneuver segmenting and analysis grouping
- General pre-processing tools (DATPAR)
  - basic math operations, unit conversions, wild point editing, filtering, smoothing, differentiation, axis rotation / translation, signal time synchronization
- Specialized flight test tools
  - total force and moment aerodynamic reconstruction
  - sensor measurement translation
- Kinematic consistency (NAVIDNT)
- Equation error identification (Athena)
- Non-linear least squares output error identification (LSIDNT)
- Capable of hosting fully non-linear 6 DOF simulations

DATA PRE-PROCESSING

- Maneuvers examined and anomalies removed (DATPAR)
  - data dropouts and signal wrapping
- Sensor calibration studies (NAVIDNT)
  - produce kinematically consistent data sets
- Imperative histories computed (DATPAR)
  - dynamic pressure, true airspeed, Mach, stability axis angular rates...
- Standalone updated TF-34 engine model hosted within IDEAS
  - produces required body axis thrust forces and moments
- Baseline S-3B simulation with updated WAB hosted within IDEAS
  - loaded, trimmed to maneuver initial conditions, and propagated
  - produces appropriate WAB histories
  - preliminary look at baseline OFT aerodynamic strengths / weaknesses
- Total aerodynamic forces and moments reconstructed (DATPAR)
  - transfer of all moments to reference aerodynamic center

AVAILABLE PID MANEUVERS

- 7 flights containing identical PID maneuver blocks
  - blocks vary in altitude, airspeed, and flap / gear configuration (120-325 kts / 5,000 - 15,000 ft)
  - blocks include all axis control doublets / 3-2-1-1's, bank to bank roll attitude captures (w/ and w/o aileron-spoiler interconnect active)
- 56 individual PID maneuver segments consolidated within IDEAS
  - 5 longitudinal analysis groups
  - 5 lateral-directional analysis groups
- IDEAS analysis groups include
  - cruise flaps / gear up
  - cruise flaps / gear down
  - maneuver flaps / gear up
  - takeoff flaps / gear down
  - landing flaps / gear down

EQUATION ERROR PROCEDURES
(Athena)

- Represents aerodynamic forces / moments as a linear buildup of time independent aerodynamic coefficients

  $$\mathbf{y} = \mathrm{A}\,\mathbf{p} + \mathbf{v}$$

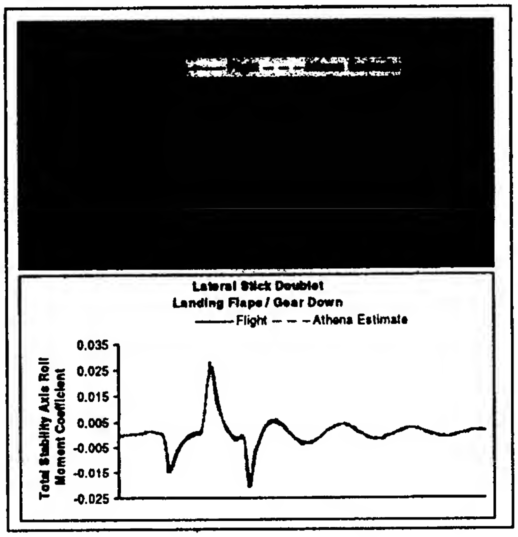
- May extract complete or incremental model
- Spline basis functions
  - allow estimation of non-linear coefficient functionalities
  - requires definition of representative knot locations [f(model regressors)]
- Provides fit quality statistics
  - Theil's inequality fit percentage (F)
  - fit error broken into bias (U_b), variance (U_v), and covariance (U_c) proportions
- Analyzes multiple maneuver segments at once for global modeling
- Fast / single pass algorithm provides good base model structure
- Can result in biased estimates

EQUATION ERROR PROCEDURES
(Athena)

- Cruise condition model structure developed for all axes (Z,M,L,N,Y)
  - drag maintained at original OFT formulation
  - cruise flap setting analysis groups analyzed
- Simple models initialized and Athena fit statistics monitored
  - manually varying model structure
  - manually varying coefficient functionality
- Estimation of flap / landing gear effects
  - base cruise model frozen
  - incremental coefficients added to base model terms
  - Athena fit statistics monitored
- Sample total rolling moment coefficient structure

$$\boxed{\begin{aligned} C_l = {} & C_{l_o}(M) + \left(C_{l_\beta} + \Delta C_{l_\beta}(\delta_F)\right)\beta + C_{l_{\delta_r}}(\alpha)\delta_r + \left(C_{l_{\delta_a}} + \Delta C_{l_{\delta_a}}(\delta_F)\right)\delta_a + \\ & \left(C_{l_{\delta_{sw}}} + \Delta C_{l_{\delta_{sw}}}(\delta_F)\right)\delta_{sw} + \left(C_{l_r} + \Delta C_{l_r}(\delta_F)\right)\frac{r_s b}{2V} + \left(C_{l_p}(\alpha) + \Delta C_{l_p}(\delta_F)\right)\frac{p_s b}{2V} + C_{l_{\delta_{tr}}}(\alpha)\delta_{tr} \end{aligned}}$$

TOTAL COEFFICIENT COMPARISON



Athena Fit Statistics
(Cruise Flaps / Gear Up)

$F = 86.8\%$
$U_b = 0\%$
$U_v = 1.7\%$
$U_c = 98.3\%$

Athena Fit Statistics
(Land Flaps / Gear Down)

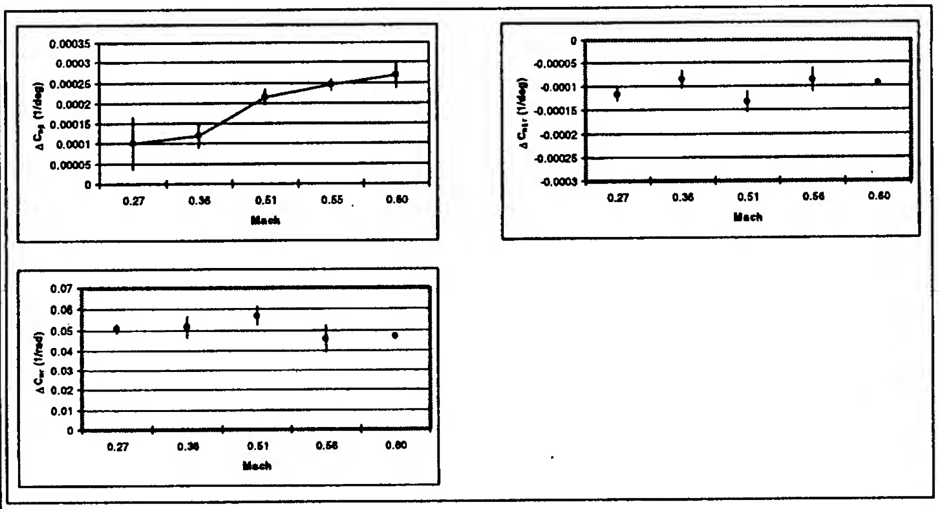
$F = 88.4\%$
$U_b = 0\%$
$U_v = 0.8\%$
$U_c = 99.2\%$

OUTPUT ERROR PROCEDURES (LSIDNT)

- Updated aerodynamic model included in IDEAS 6 DOF simulation
- Simulation trimmed and control surface positions overridden with flight data for varying PID style maneuvers
- Comparisons made between flight data and updated simulation output
  - provides clues as to where model adjustments may be necessary
- Final adjustments determined via estimation of incremental coefficients applied to Athena generated model terms using LSIDNT
- Consider example where yaw coefficients required correction

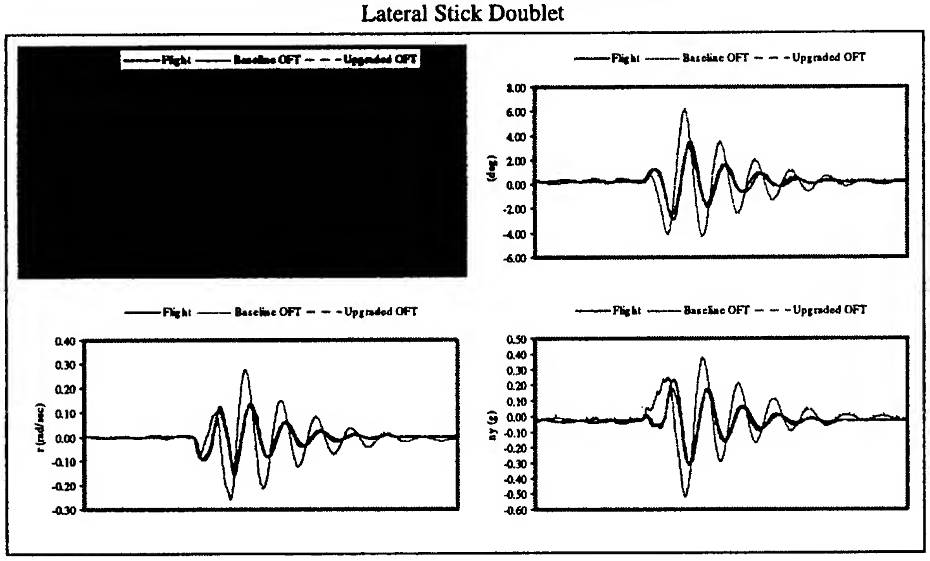
$$\Delta C_n(\beta) = \left(C_{n_{\beta_{Athena}}} + \Delta C_{n_{\beta_{Flt.Der.}}}\right)\beta$$
$$\Delta C_n(r_s) = \left(C_{n_{r_{Athena}}} + \Delta C_{n_{r_{Flt.Der.}}}\right)\left(\frac{r_s b}{2V}\right)$$
$$\Delta C_n(\delta_r) = \left(C_{n_{\delta_{r_{Athena}}}} + \Delta C_{n_{\delta_{r_{Flt.Der.}}}}\right)\delta_r$$

RESULTING CORRECTIONS



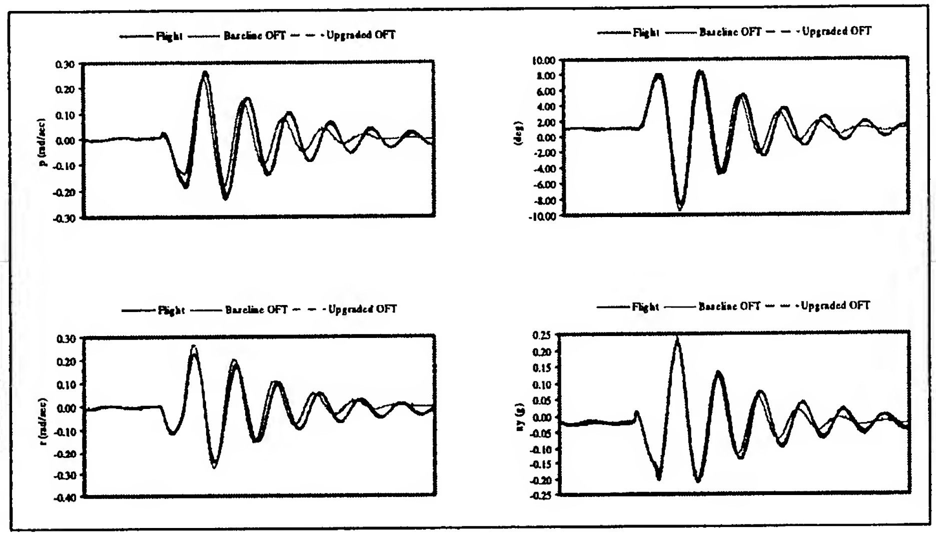
LATERAL COMPARISON

Lateral Stick Doublet



DIRECTIONAL COMPARISON

Directional Pedal Doublet



LONGITUDINAL COMPARISON

Longitudinal Stick Doublet